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A Study Of The Electrodynamometer.

A STUDY OF THE ELECTRODYNAMOMETER

BY

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B. A. University of Denver, 1913

M.A. University of Denver, 1914

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF ARTS

IN PHYSICS

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1916

1916
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UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

June 1 1916

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY ELEANOR FRANCES SEILER

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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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I INTRODUCTION

In this investigation the primary object was to determine the working conditions under which the best results may be expected when the classic Siemens type of electrodynamometer is used as a wattmeter. The agreement of the results obtained, in some cases, is not as good as is possible with the apparatus used, the reason being that the values of certain quantities were varied simply to find whether or not the change would prove to be advantageous. The instrument to which particular attention was given, is one of six constructed in the Laboratory of the University of Illinois for use in a course in Electrical Measurements.

II DESCRIPTION OF APPARATUS

The Siemens electrodynamometer, No.37640' is pictured in Fig.2. A diagrammatic sketch of its working parts is shown in Fig. 1. The instrument consists of the following parts:

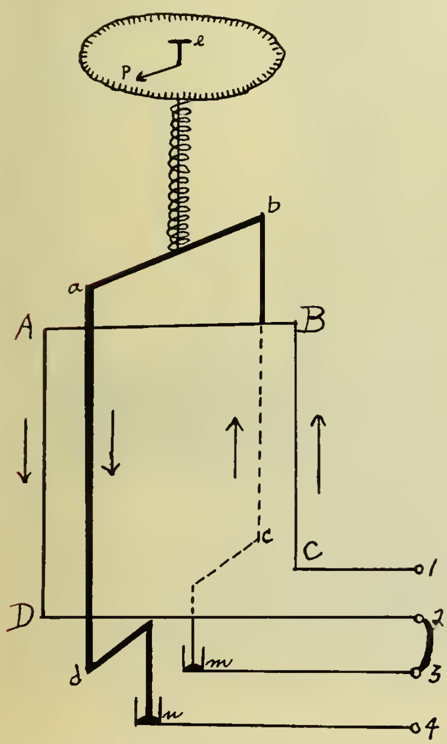
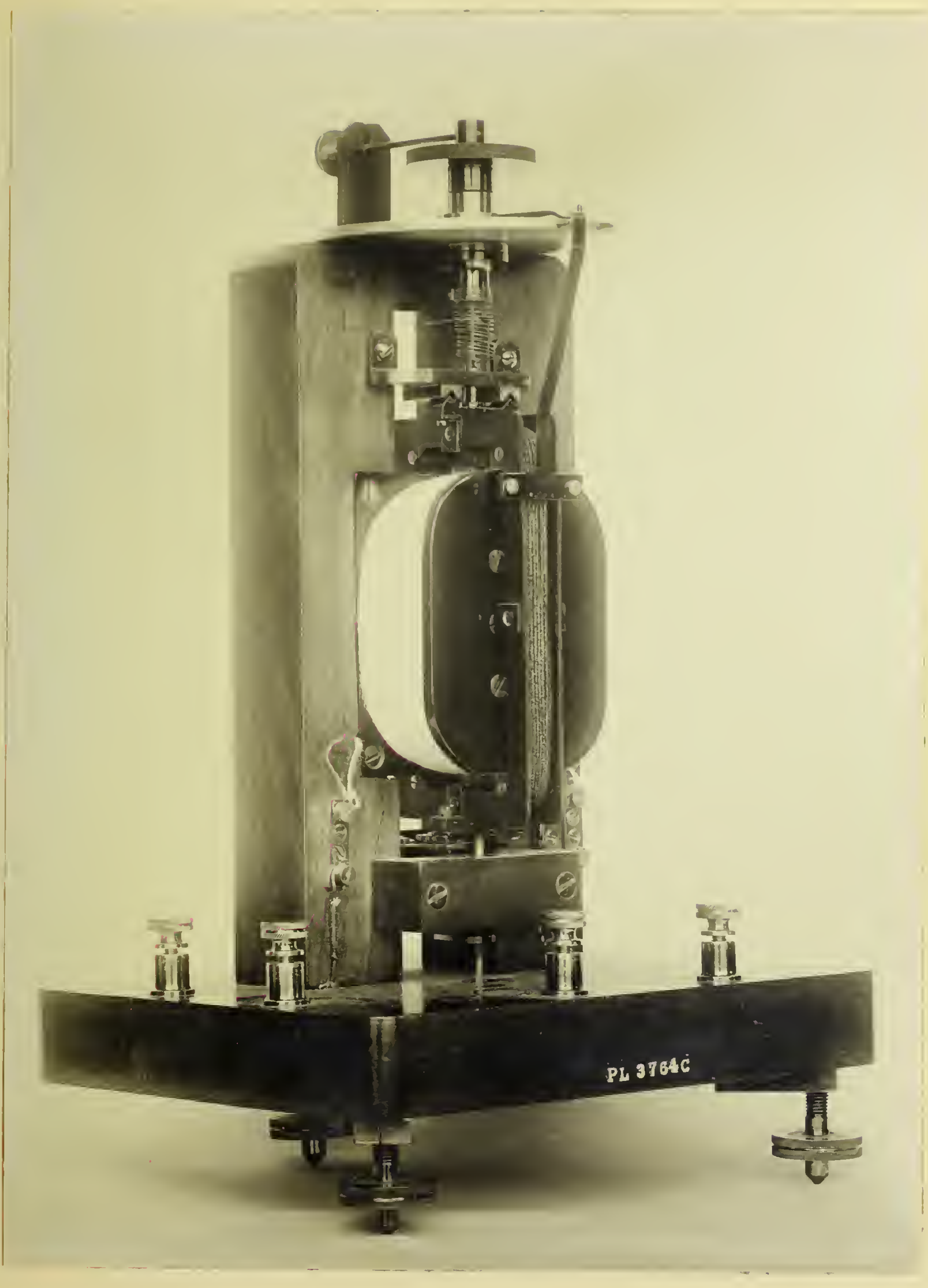


Fig. 1

The movable coil, having 24 turns of No.18 B & S copper magnet wire is wound upon a rectangular frame abcd, whose dimensions are 7 x 12.5 cm. It is suspended by a torsionless silk fibre, whose upper end is fixed to a torsion head e, the latter being provided with a pointer p which can be moved round a graduated dial.

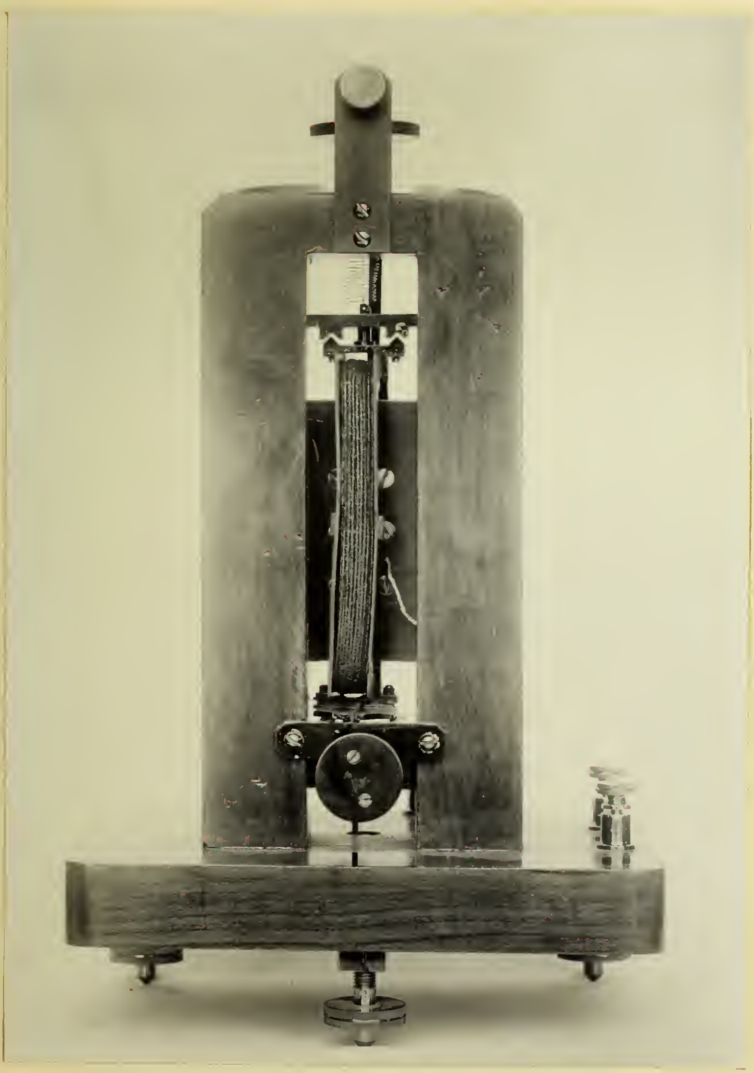
The dial, 10 cm. in diameter, is made of aluminum and has 200 equally spaced scale divisions on its

Fig. 2



Oblique View of Electrodynamometer No.3764C'

Fig. 3



Rear View of Electrodynamometer No.3764C'

Fig. 4

Top View of Electrodynamometer No.37640'

circumference.

<u>The Spring</u>.- One end of a steel spiral spring, s, of 16 turns is also attached rigidly to the torsion head. In this arrangement the number of divisions to which the pointer is directed evidently indicates the twist given to the spiral spring. This chronometer spring is made of the very best and most carefully tempered steel. When not stretched beyond the limit of elasticity, or when not kept in a strain for a longer time than is necessary for taking a reading, the elasticity is perfect, and Hooke's Law is obeyed. Consequently the pointer p should not be left at any other place but zero for a considerable length of time. Otherwise a slight deformation of the spring may result, which will in time disappear, but not immediately. The elastic modulus which is brought into play in the use of such a spiral spring is somewhat similar to that which is operative when a beam is bent. The spiral is not drawn out, but is twisted round and bent slightly into a smaller radius. Under prolonged strain a very slight deformation occurs, which disappears gradually on the removal of the stress, and this deformation is a function of the stress and the time under which the elastic body is submitted to that stress.

This effect was quite noticeable in instrument 3764C'. The pointer had been turned half way round the scale and left there for three days. When it was brought back to the zero mark the pointer attached to the movable coil did not coincide with it, but was one scale division off. In the course of ten or twelve hours, however, both pointers came to rest at the zero point again.

Three electrodynamometers were carefully examined in regard to the action of the spring before one was finally selected. The spring

when properly made should wind up uniformly and present the appearance of a helix of uniform diameter, with no two adjacent convolutions touching each other. Two of the springs tested would not do this, but when subjected to a torsion, they would take on an irregular shape, showing a noticeable contraction near the middle with a shifting of the planes of the individual turns from the horizontal position.

Changes of temperature also slightly affect the permanency of the steel spring. Professor W. Kohlrausch[1] on his experiments of this nature found that an increase of 18°F, when a brass spring was used, raised the indications of a Siemens torsion galvanometer about one-tenth percent, so that the reduction in the elasticity of the spring is apparently almost equal to the decrease in moment in the magnet. Further experiments on loaded springs confirmed this conclusion, and showed that steel was preferred to either brass or German silver. Thus there is sufficient evidence to lead us to believe that the selection of a highly tempered steel spring as a means of weighing the electrodynamic attraction of coils traversed by currents will not be found to lead to appreciable error.

The steel spring, on the other hand, introduces a small error, in that, it being a conductor in a magnetic field, its permeability changes the uniformity of the field in which the movable coil swings. Brass or German silver springs being nonmagnetic would be free from this effect.

To the rectangular frame of the movable coil is fixed a pointer, the end of which just laps over the edge of the graduated dial.

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1 Electrician, March 25, 1887

In this particular type of instrument the movable coil encircles the fixed coil ABCD, whose plane when a reading is taken is always at right angles to that of the movable coil. This coil, wound on a rectangular hard rubber bobbin whose dimensions are 3 x 6 cm., had as first made, 475 turns of No.20 B & S copper magnet wire and was later changed to 1259 turns of No.25 B & S wire. The instrument in its first form we shall for convenience call by the laboratory number 3764C, while the latter form by 3764C'.

The two ends of the fixed coil are connected to the terminals 1 and 2, while connections are made with the movable coil by having the ends of the coil dip into small mercury cups m and n, which are in turn joined to the terminal binding posts 3 and 4.

The base-board upon which these coils are mounted is a piece of polished cherry wood of dimensions 18 x 21 x 3 cm. It carries three levelling screws, two on the front corners and one in the center of the rear edge.

Best Shape for Movable Coil.- It has been shown by Mather[2] that the best shape of the section of a movable coil perpendicular to the axis about which it turns is that of two tangent circles as shown in Fig. i, the shading indicating that the current is flowing in the opposite direction in each side, and AB being a median line. The efficiency for this form over that used as shown in Fig. ii he has calculated to be

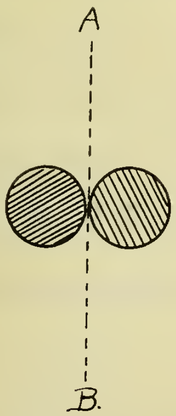


Fig. i

2 On the Shape of Movable Coils Used in Electrical Measuring Instruments., T. Mather, Phil.Mag., (5), 29, 1890, 434.

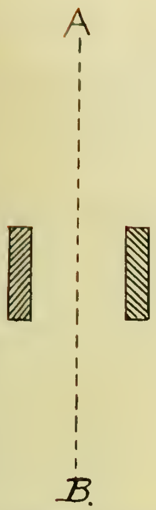


Fig. ii

very much greater. For the deflecting moment per unit moment of inertia he obtained a value of 1.02 for the first arrangement, while only .4 to .5 was found for the second case, which is the one in common use. In the Siemens Electrodynamometer, however, for fairly large currents it would be difficult to make the coil of the best shape, owing to the space required for the mercury cups. Nevertheless a much closer approximation to this shape than the one often employed could be used. In the case of mercury cups, it may be noted that, owing to friction and viscosity, a certain minimum control is necessary to give the required definiteness to zero. The mercury cups also make the use of such an electrodynamometer impossible at sea, hence two other methods have been devised by means of which the current can be led in and out of the movable coil. These are, by wires which also serve as control, thus dispensing with the spiral spring, and by flexible wires independent of control.

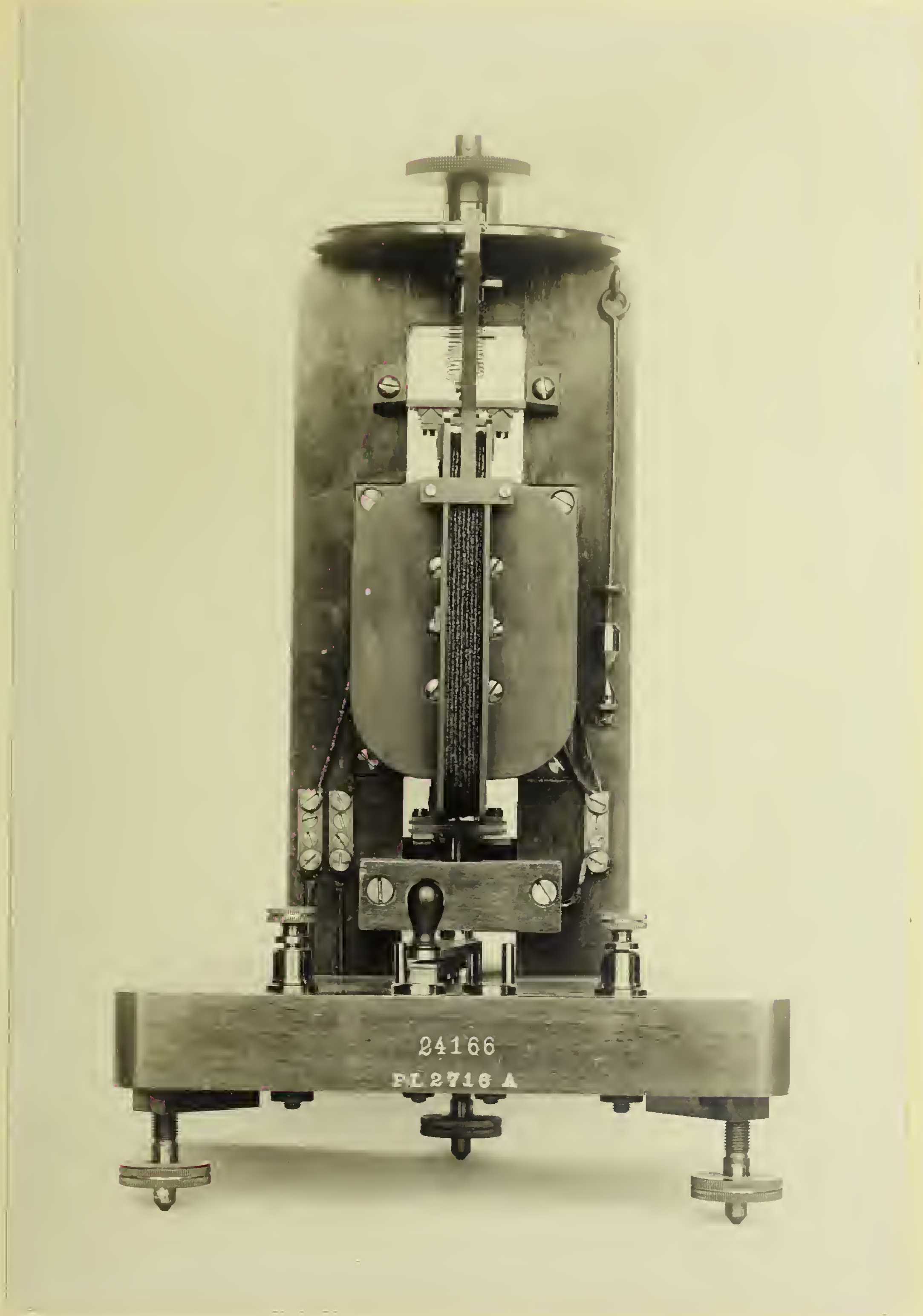
Four minor details remain to be described. Two small stops are placed horizontally in the rim of the dial 0.7 cm. on either side of the zero point. These keep the vibrating coil confined to a movement of about 1.5 cm. and thus facilitate in bringing the coil to rest. The suspension thread at the upper end passes through a small eyelet at the end of a shaft which is supported by friction in a slot of hard rubber rigidly fastened to the back of the wooden upright. A milled head attached to the end of the shaft enables one to raise or lower the movable coil. A set screw, placed in the ring to which the pointer is attached, allows the zero point to be accurately set. A

very convenient arrangement is a device for clamping the movable coil into a rigid position, thus protecting the suspension and making the instrument portable. It consists of a thumb screw placed in the back of the instrument below the lower end of the movable coil. When the screw is advanced, it pushes against a lever, which in turn pushes against the lower part of the coil and raises it until two notches, cut in a brass bar fastened to the upper part of the coil, exactly fit into two similar notches in a brass strip supported by the wooden upright.

This completes the description of the particular electrodynamometer which was taken for the subject of this study, and which, for this reason, has been given in some detail. Two other instruments were subjects of investigation also, the first No.2716A is an electrodynamometer made by Siemens and Halske, after which the one described above was patterned. The essential differences between this one and the former are three. It has but two binding posts, the fixed and movable coils being permanently connected in series, so this instrument is usable as an ammeter only. It has two separate coils wound on the stationary bobbin, either one of which can be used at will, by simply moving a sliding contact maker from one brass disc to the other, the left one being connected to the coil of heavy wire and few turns for use with large currents, and the right one to a coil of finer wire and greater number of turns, for use in the measurement of smaller currents. The dial is made of brass with a paper scale, reading degrees, pasted on it.

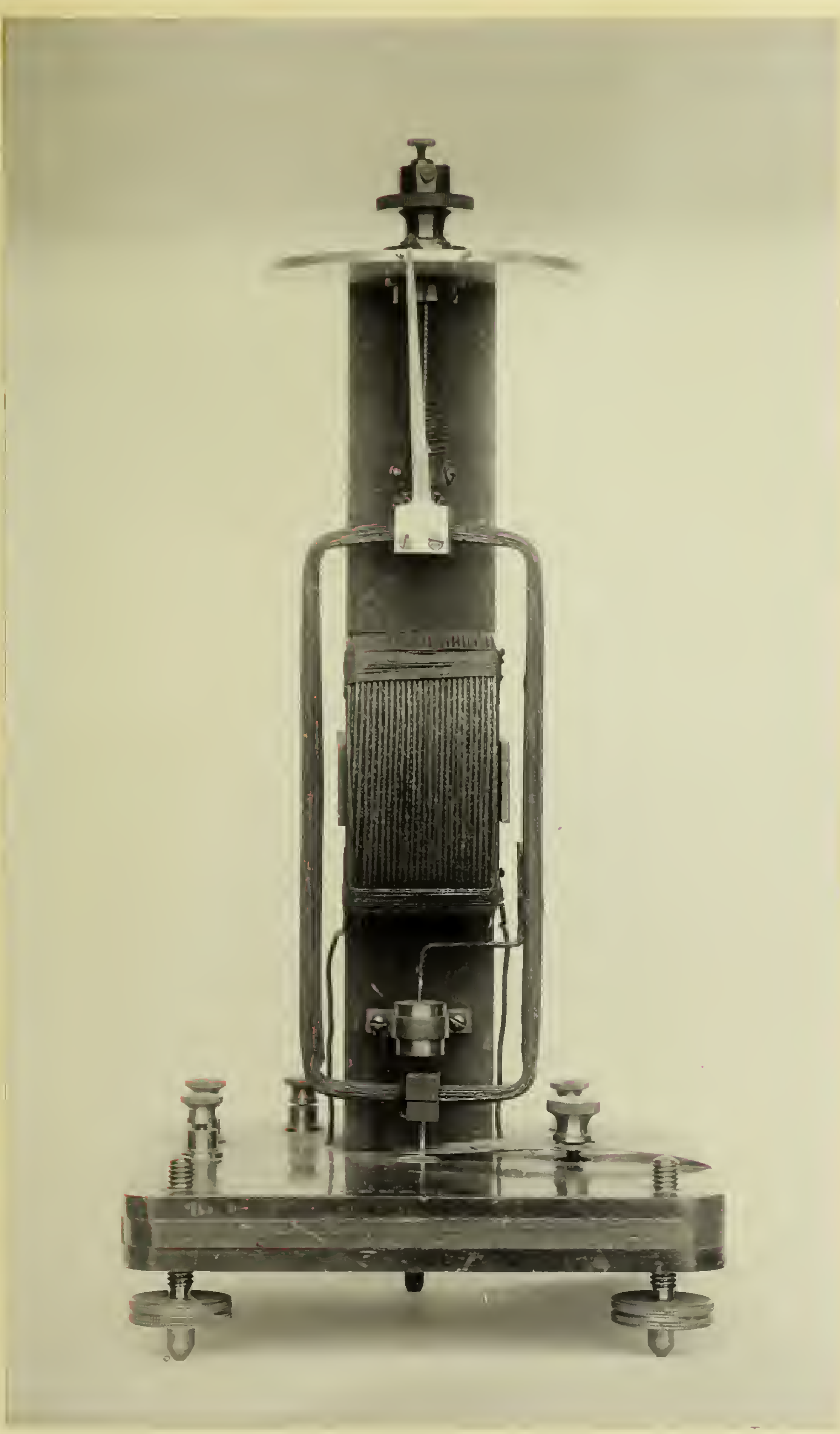
The third electrodynamometer used, No.2323, was also made in this laboratory. It was built a number of years ago and is much cruder in construction than either of the other two and the essential

Fig. 5



Front View of Electrodynamometer No.2716A

Fig. 6



Front View of Electrodynamometer No.2323

differences between it and No.3764C are,- the movable coil is of a great many turns of fine wire, not wound on a bobbin, but kept in rectangular form by black shellac; the spring is made of brass, is heavier and has more convolutions, the device for holding the movable coil rigid is simpler and less effective, the suspending fibre is much coarser and a peg is substituted for the rear levelling screw.

Other Types of Electrodynamometers.- Three other types of electrodynamometers of especial interest will now be described, and their particular advantages indicated.

Rowland Electrodynamometer.- An excellent instrument is the one designed by Henry A. Rowland of Johns Hopkins University. In combination with a specially designed shunt box, it is particularly adapted to the measurement of alternating currents or direct currents from .001 to 50 amperes, for the measurement of volts, alternating or direct, from .1 to 500 or more, and watts from .01 to 25000. The apparatus may also be adapted to the measurement of self and mutual inductances and capacities. With some accessory apparatus, Professor Rowland describes other measurements as being easily made with the dynamometer, such as the hysteresis of iron and losses under actual conditions, measurement of liquid resistance, and detection of short circuits in coils.

The instrument consists of two pairs of fixed coils, together with a movable coil. The one pair of fixed coils is on the outside of the case and is used for carrying currents as great as 50 amperes; the other pair, on the inside of the case is suitable for currents up to .1 of an ampere. The movable coil is adapted to currents as large as .1 of an ampere. The fixed coils are in such a position

that the movable coil turns in a nearly uniform field of force throughout the angle through which the coil turns. A mirror is attached to the movable coil and a telescope and scale are fastened at a fixed distance from it, on an arm which can readily be swung out of the way when the instrument is not in use. As no lateral adjustment of the scale is provided, the coil is brought to zero by turning a micrometer screw which rotates the suspension tube. Hence when adjustment is made to read zero with no current flowing, the coil is always in the same position in the field. Thus, it is evident that the constants of the instrument having once been determined, do not alter. The movable coil system has two coils connected to form an astatic combination, so that the instrument when used with direct currents will not be affected in its deflection by the earth's field.

The shunt box consists of a number of manganin resistances wound on micanite cards and slate, in such a manner as to eliminate inductance and capacity. In its use, either with direct or alternating currents, the various resistance combinations and arrangements which are necessary in the different measurements, can be secured by moving the dials on the top of the box in accordance with definite given instructions. There are four such dials,- E, gives the different resistances which can be thrown in series with the movable coil, D commutates or reverses the direction of the current flowing through the movable coil, A, gives the resistances used in the measurement of volts and watts.

This shunt box is placed on the floor to the right of the operator, and is connected to the dynamometer on the wall by four flexible connecting cords.

The Absolute Electrodynamometer.- There is a continuous effort on the part of physicists to construct a satisfactory primary standard of current based on the electrodynamometer principle, the constant of which standard may be deduced theoretically in C.G.S. units from its geometrical dimensions. One such "absolute" electrodynamometer was designed by Pellat. It consists of a large stationary coil and a small coil fastened to the beam of a delicate balance. When the instrument is operated, the large coil is moved along to inclose the small one. The two coils are connected in series and the electro-magnetic couple of the current is balanced by a weight on the scale pan. The current corresponding to a certain net weight on the pan is theoretically calculated from the dimensions of the coils. Hence we see that the instrument is a primary standard in the true sense of the word. An instrument of this type is very expensive, for the coils must be finished with the greatest accuracy, and the entire apparatus made of materials which will not change their dimensions with time or temperature.

It is interesting to compare three primary standards: (a)standard cell, (b) standard resistance, and (c) standard electrodynamometer. When connected up as shown in Fig. 7 any two of them may be checked by the third. The current is measured by the absolute

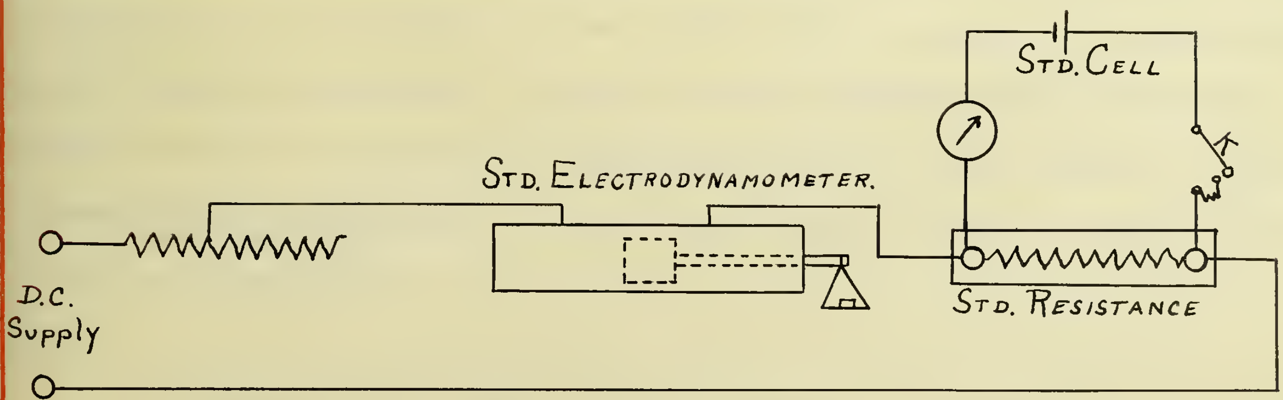


Fig. 7

electrodynamometer, and also by the standard resistance and the cell. The value of the current is adjusted by the rheostat R, so that the galvanometer shows no deflection when the switch K is closed. Assuming, for example, that the electrodynamometer is correct, and the exact value of the resistance of the shunt is known, the e.m.f. of the standard cell may be calculated as the product of the current and the resistance. This is the method by which the latest determinations of the e.m.f. of Weston and Clark standard cells were made.[3]

Lord Kelvin Current Balance.- One other instrument depending on the electrodynamometer principle for its action, and which is of major importance, is the Lord Kelvin Current Balance.

It differs from the absolute electrodynamometer in this respect,- that whilst in the former the current is calculated from the dimensions of the apparatus and the balancing weight employed, in the latter, the constant of the instrument is determined by the aid of a copper voltameter. On account of the invariability of this constant the balance may be employed as a secondary standard current measuring instrument.

III THEORY OF THE SIEMENS ELECTRODYNAMOMETER

General.- The electrodynamometer depends for its action on the fact discovered by Ampere, that mechanical forces exist between conductors carrying electric currents when these conductors occupy certain relative positions. If they are two parallel wires through which currents are passing, then the wires are drawn together if the currents are in the same direction and pressed apart if they are in opposite directions.

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3 Bulletin No. 1 (Vol.2) 1906, Bureau of Standards, Dr. Guthe

When Used as an Ammeter.- Now, if the two coils be connected together in series as shown in Fig. 1, then a current entering at terminal 1, and leaving terminal 4, will traverse the two coils, and the current passing from C to B will attract the current passing from c to b, and will repel the current going from a to d. A similar action takes place with reference to the current flowing from A to D: consequently the movable coil, under the influence of the forces, will tend to turn about its axis, in an anti-clockwise direction.

Another way of looking at this is to consider each coil as a magnet possessing polarity, and then the action between the poles clearly causes rotation. The front face of the fixed coil, as the current passes through it, is of N polarity and the right face of the movable coil is equivalent to the North pole of a magnet. The two remaining faces are of S polarity and consequently attractive and repulsive forces are set up.

If the current enters at 4 and leaves at 1, then the rotation is still in the same direction, for the direction of flow of current, or polarity of the face in each coil is reversed. However, reversing the direction of the current through one coil only, will reverse the direction of the deflection. This turning of the movable coil is similar to the deflection of the coil of a D'Arsonval galvanometer. But in the electrodynamometer the magnetic field is not due to a permanent steel magnet, but is produced by the current flowing in the fixed coil. Thus the deflection, D, depends upon the current I in the fixed coil as well as upon the current i in the movable coil: that is,

$$Ii \propto D \tag{1}$$

or changing the proportionality sign to one of equality, we have

$$Ii = K^2D \tag{2}$$

where K^2 is a constant, including all the factors relating to the size and form of the coil, etc., and also including the restoring couple of the suspension.

If the same current flows through both coils in series,

$$I^2 = K^2D \tag{3}$$

or

$$I = K\sqrt{D}. \tag{4}$$

The coil is brought back to its zero position by the torsion of the helical steel spring s, and D is the number of divisions of the scale which measures the amount of this torsion.

When a coil carrying current is suspended in a magnetic field, for example the earth's field, it tends to turn so as to add its magnetic field to the other. If the electrodynamometer is set in such a position that the earth's field is added to its own, evidently the deflection will be increased a corresponding amount. If the two fields were opposed to each other the deflection would be lessened. This effect can be eliminated by turning the instrument so that the plane of the movable coil is east and west.

In all of the experimental work done, this precaution was taken, as was also the placing of the ammeter and voltmeter at a permanent and sufficient distance from the electrodynamometer so as to minimize the effect of their magnetism on the magnetic field of the instrument.

We see by equation (3) that once K is determined, the electrodynamometer acts as an ammeter. This constant may be determined for the entire range of the instrument, which will be discussed under the heading of <u>Calibrations</u>, or it may be obtained for one particular value of a current as measured by a voltameter. This latter method

was followed with instrument 3764E. The following table shows the results:-

TABLE 1

The Determination of the Constant of Electrodynamometer No.3764E by Means of a Copper Voltameter

Time in Minutes	D	$\sqrt{D}$	Check I from Am
10:45			
10:50	123.0	11.09	.6625
10:55	122.9	11.08	.6625
11:00	123.0	11.09	.6625
11:05	123.0	11.09	.6620
11:10	122.6	11.09	.6610
11:15	122.1	11.07	.6610
11:20	121.1	11.04	.6600
11:25	121.1	11.00	.6600
2700 sec.		Average 11.575	Avr. .66144

$$I = \frac{\text{Gain in Wgt.}}{\text{Time in sec. x .0003288 gms}} = \frac{.547}{.78912} = .693 \text{ amperes}$$

$$K = \frac{I}{\sqrt{D}} = \frac{.693}{11.575} = .059$$

Here the "gain in weight" refers to the amount of copper deposited on the cathode of the voltameter in the given length of time and the number .0003288 is the electrochemical equivalent of copper, i.e., the number of grams of copper deposited per second per ampere of current passing through the cell.

The above table shows that the instrument was well adapted as a measurer of current, for the current as measured by the ammeter checked well with the more accurate value as obtained by the vol-

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]			[illegible]
			[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]
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tameter.

A good feature of electro-dynamometers used as ammeters is that they are accurate and sensitive; moreover, because of the fact that they have stationary coils instead of permanent magnets, they may be calibrated with direct current and used with alternating current. Their serious drawback is that they are not direct reading and cannot be used on commercial switchboards. The presence of mercury, and the necessity for levelling make them inconvenient to handle, even in ordinary work. Another disadvantage is that they have no provision for damping, and require some skill in taking readings, especially with fluctuating currents.

<u>When Used as a Wattmeter, with Direct Current</u>: A wattmeter is an instrument for measuring power developed in a circuit. The name "wattmeter" comes from the name "watt", which is the practical unit of power, in the volt-ampere-ohm system.

Power expended in a direct-current circuit is equal to the product of the current delivered times the pressure at which it is supplied; in practical units

$$\text{Watts} = \text{amperes} \times \text{volts}$$

or with the customary notation

$$W = EI \tag{5}$$

An ammeter and voltmeter connected as shown in Fig. 8 for the measurement of resistance, will at the same time give the power expended in R_x, for from equation (5) we readily see that all we have to do is to take the product of the ammeter and voltmeter readings and thus secure the

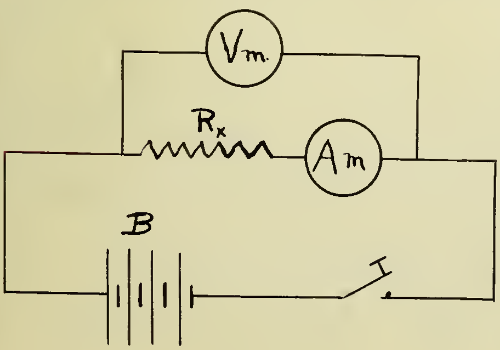

Fig. 8

power consumed in the resistance.

This result can be expressed in a different form. If in place of a direct reading voltmeter there had been a large resistance R_1 (as shown in Fig.(9) in series with a mil-ammeter for measuring the current, i, through it, then

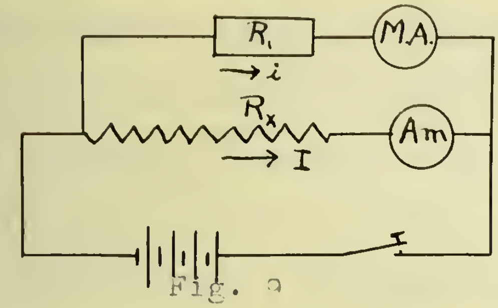

Fig. 9

and

$$E = Ri \tag{6}$$

$$W = RiI \tag{7}$$

In this form it is seen that the measurement of power implies the product of two currents; and in equation (2) it was seen that an electrodynamometer is an instrument for measuring the product of two currents. Therefore the electrodynamometer can be used as a wattmeter, if it is connected into the circuit in the proper manner.

Let R_x, Fig.10, be the circuit in which the power is to be

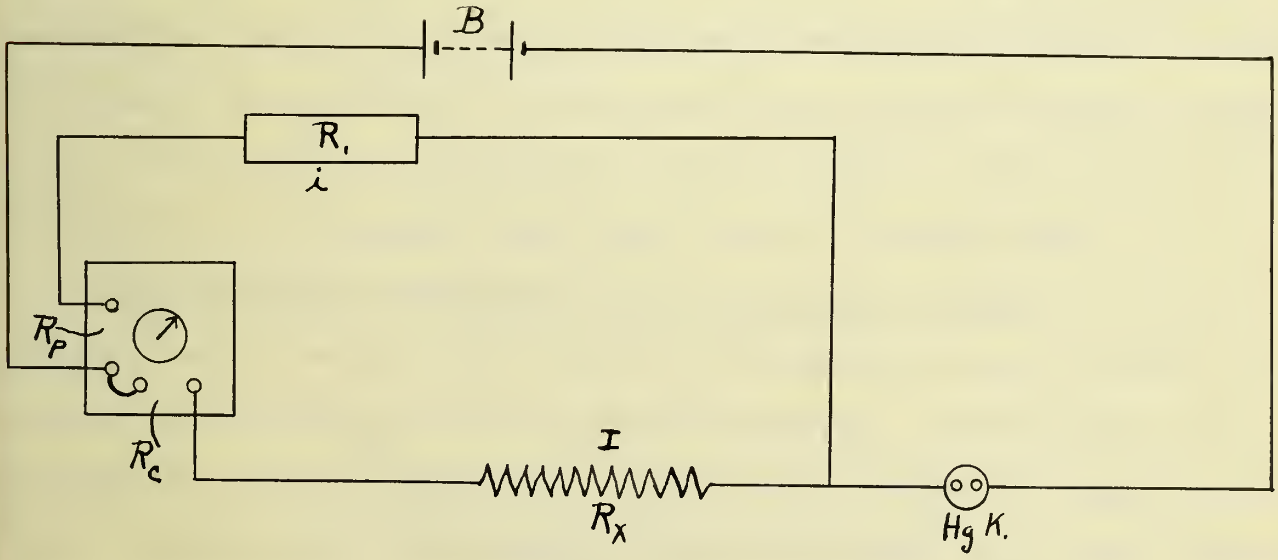

Fig. 10

measured, it may be a bank of incandescent lamp, tin resistance, or any kind of translating device. The low resistance or current coil, R_c, of the electrodynamometer is connected in series with R_x as was the ammeter of Fig. 8. The other coil, R_p, called pressure coil, is

joined in series with a resistance (from 100 to 9000 ohms) to form a shunt circuit of high resistance, and this is connected in the place of the voltmeter to measure the fall of potential over R_x and R_p. For let i denote the value of the current through this shunt circuit, and R, which is equal to R_1+R_p, its resistance. The fall of potential is then Ri, as in Fig. 9. This current i through one coil of the instrument, together with the main current I through the other coil, will result in a deflection D, proportional to the product of the two currents. From equation (2) of the electrodynamometer where $Ii = K^2D$ and from equation (7), the power being expended in R_x is $W = RiI$, we get

$$W = RiI = RK^2D \tag{8}$$

which is the equation of the electrodynamometer when used as a wattmeter. When the constant, K, of the instrument is known, then RK^2 becomes the factor for reducing the scale readings to watts. In case this factor is unity, as it can be made by giving the correct value to R_1, the wattmeter is said to be direct reading. This particular value of R_1 in instrument 3764C' was found to be 753 ohms.

<u>When Used as a Wattmeter with Alternating Current</u>.- As previously stated, we know that the electrodynamometer may be used to measure alternating as well as direct currents. In this case, the presence of self-induction and capacity so modifies the relations for direct current, that the product "effective volts" e_{eff} times "effective amperes" i_{eff} is not equal to the true average watts expended in the circuit. The relation $w = ei$ is, however, always true for instantaneous values of current (i) and voltage (e); in other words, iedt represents the electrical energy delivered to an alternating current circuit during an infinitesimal interval of time dt. The average

energy delivered in one second, or the power in watts, is then

$$W = \frac{I}{T}\int_0^T i\ e\ dt \qquad (9)$$

where T is the time of one cycle of the alternating current. Assuming that both current and voltage vary according to the sine law, we have

$$i = I \sin mt \qquad (10)$$

and

$$e = E \sin(mt \pm \phi) \qquad (11)$$

where ϕ is the phase angle by which the e.m.f. lags behind the current, and $m = \frac{2\pi}{T}$. Substituting in (9) we obtain

$$W = \frac{IE}{T}\int_0^T \sin mt \cdot \sin(mt \pm \phi)dt \qquad (12)$$

or

$$W = \frac{EI}{2}\cos\phi \qquad (13)$$

Substituting the effective values of the voltage and the current, equation (13) becomes

$$W = i_{eff}\ e_{eff}\ \cos\phi \qquad (14)$$

Equation (14) shows that true power delivered to an alternating circuit does not only depend upon the effective values of the current and the voltage, but also upon the phase angle between the two. The expression $i_{eff}\ e_{eff}$ is sometimes called the apparent power, and $\cos\phi$, the ratio of the true power to the apparent power is called the power factor.

Thus we see that in order to measure the true power in an alternating-current circuit, it is necessary to have a measuring device which automatically accomplishes the integration required by equation (9) and gives the average value of w. Such an instrument is an electrodynamometer. All we need to do is to connect the pressure coil in series with the circuit, as in an ammeter, and the current coil across the circuit with a high non-inductance resistance in series with it. This high resistance is put in so that there is

practically no current flowing through the pressure coil to the loss of current in the main circuit.

If the moving part of the instrument had no inertia it would vibrate with the fluctuations of the instantaneous values of energy, but with the ordinary frequencies of alternating currents, these changes follow in such rapid succession that the current coil assumes a position corresponding to the average impulse, that is, it automatically integrates the power over the cycle, according to equation (9).

In using an electrodynamometer in this way, it is important that the periodic time of the alternating current be small compared with the free time of vibration of the movable coil.

One factor hinders the instruments used in this investigation from being used with alternating currents, and that is the use of brass near the coils which are traversed by the alternating current. When there are such metal parts, the alternating current in the fixed coil sets up eddy currents in them, and the eddy currents are nearly in opposition as regards phase with the currents producing them. Hence the eddy currents react on the movable coil, and make the mechanical force upon it different from that which it would be if the eddy currents were absent.

When Used as a Voltmeter.- In this case both coils must be made of a large number of turns of fine wire, making the instrument very sensitive to small currents. Then by connecting a high resistance in series with the instrument it may be connected across the terminals of the circuit whose pressure is to be measured. Thus the electrodynamometer really measures the current passing through it, but by Ohm's law this is proportional to the pressure or E.M.F. at

its terminals, and the force is therefore a measure of the E.M.F.

Use as a Method For Measuring Hysteresis.-[4] G. F. Searle and T. G. Bedford have introduced the method of measuring hysteresis by means of an electrodynamometer used ballistically. The fixed and suspended coils of the instrument are respectively connected in series with the magnetizing solenoid and with a secondary wound upon the specimen. When the magnetizing current is twice reversed, so as to complete a cycle, the sum of the two deflections, multiplied by a factor depending upon the sectional area of the specimen and upon the constants of the apparatus, gives the hysteresis for a complete cycle in terms of ergs per cubic centimeter.

IV PRELIMINARY WORK

Calibrations.- Electrodynamometers: In order to use an electrodynamometer for the measurement of a current, it is necessary to know the value of the constant K, or, what is better, to have a calibration curve. Such a curve is obtained by joining the instrument

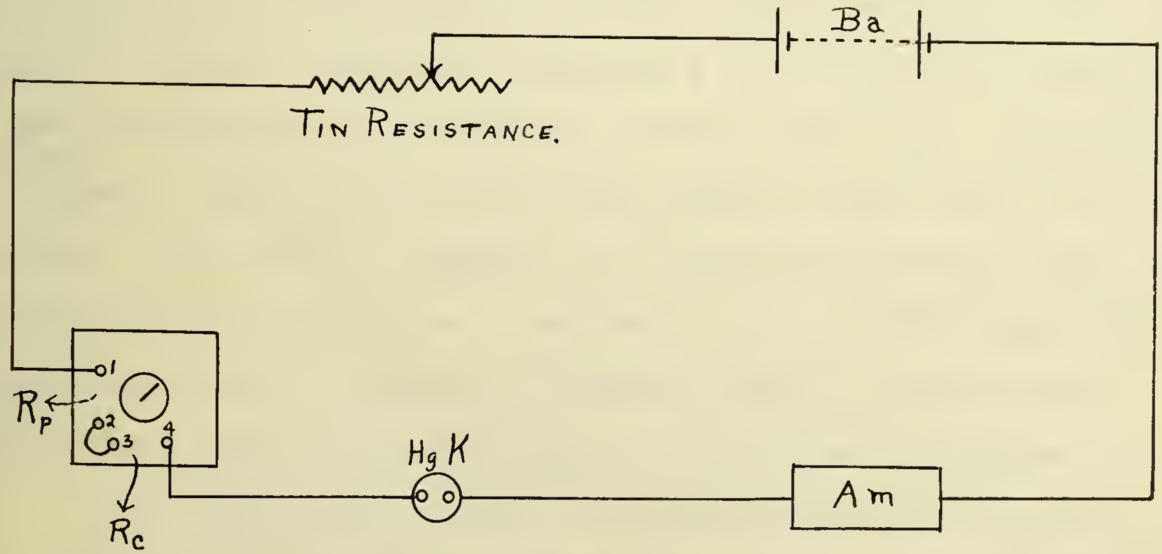

Fig. 11

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4 G.F. Searle and T.G. Bedford, Phil.Trans., 1902, 198, 33

in series with a good ammeter, one or more secondary cells, and a tin resistance for adjusting the strength of the current. By varying the strength of the current from the smallest readable deflection D, until the entire scale is traversed, a calibration curve for each instrument used is plotted, having currents as ordinates and the corresponding deflection for abscissae. This gives a horizontal parabola passing through the origin, and from this curve the value of the current corresponding to any deflection can be read.

The calibration data for six instruments was taken and the corresponding curves drawn. That of instrument 2323 is shown in Plate I, 2716A in Plate II, 3764E in Plate III, 3764F in Plate IV, 3764C in Plate V, and of 3764C' in Plate VI. In each case more points were obtained for the lower end of the curve, where its slope is changing most rapidly. All of the curves are very smooth and practically all the points in each case lie on the curve.

Instrument No.2323 has many turns of fine wire on its movable or current coil. Consequently it has a high resistance and a low range of amperes. No.3764C' also has a low range of current, because of the resistance of its fixed or pressure coil (R_p). No.2716A has the highest range of any of the instruments, being able to carry 2 amperes. This makes it usable as an electrodynamometer only, and somewhat hinders its use as a wattmeter. Nos. 3764E,F,and C have a range almost twice as great as 2323 and 3764C', but as Table I for 3764E shows, they are poorly adapted for use as wattmeters.

On the last three plates, two other curves were plotted. The one drawn with red ink shows the variation in the value of the constant K, while the other in green ink brings out the strictly linear relation between $\sqrt{D}$ and the current I. In getting the value of $\sqrt{D}$

PLATE I.

Calibration Curve for Instrument No. 2323.

I.	D.
.045	12.0
.090	15.5
.130	21.0
.170	27.5
.210	37.2
.280	58.0
.335	78.0
.370	92.5
.380	95.0

Zero Point at 10.

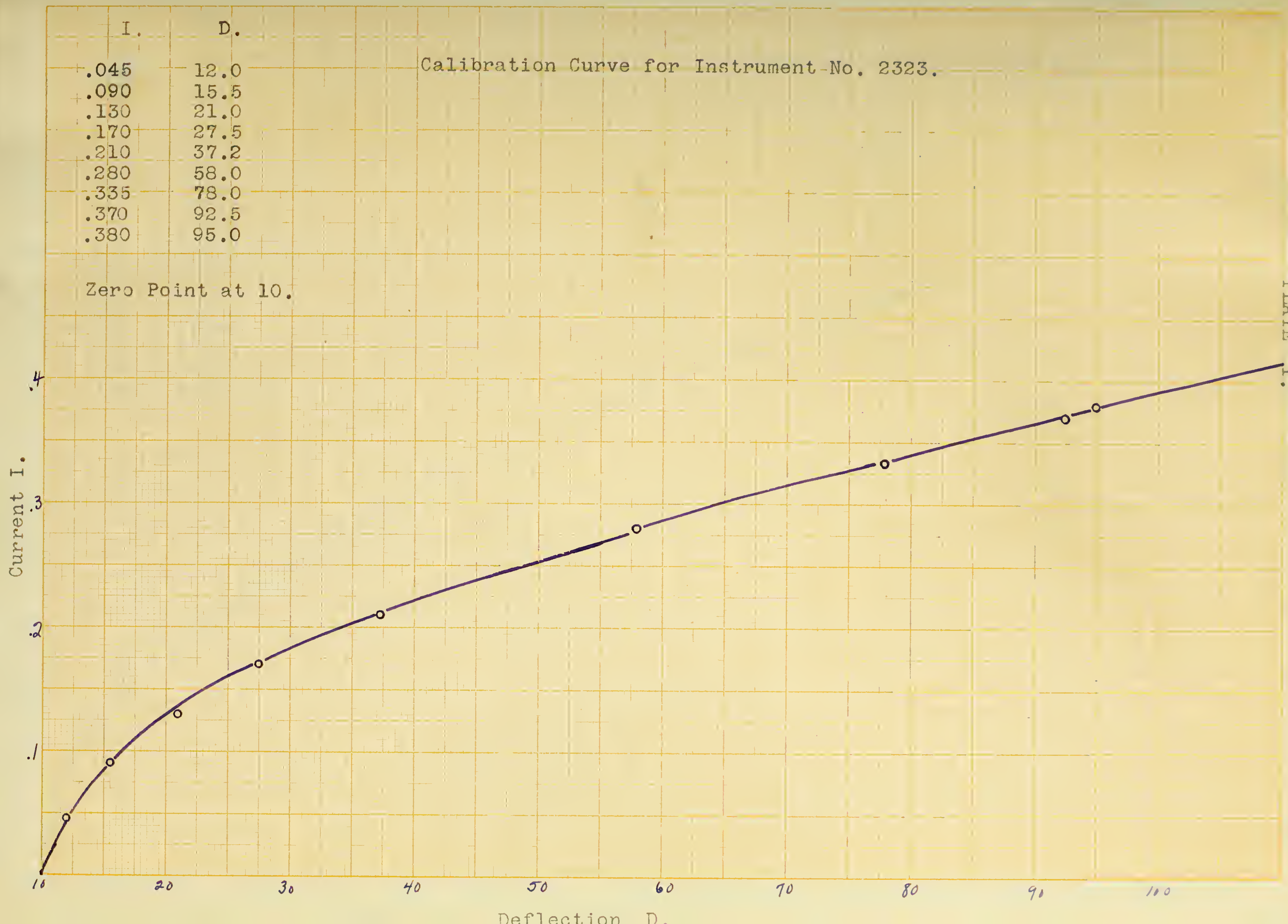


PLATE II.

Calibration of Instrument NO. 2716A.

I.	D.
.3	8.0
.4	12.0
.5	21.0
.6	28.0
.7	41.5
.8	52.0
.9	66.0
1.0	81.0
1.1	97.5
1.2	108.0
1.3	132.5
1.4	155.5
1.5	177.0
1.6	195.0
1.8	258.0
1.9	279.0
2.0	308.0
2.1	348.0

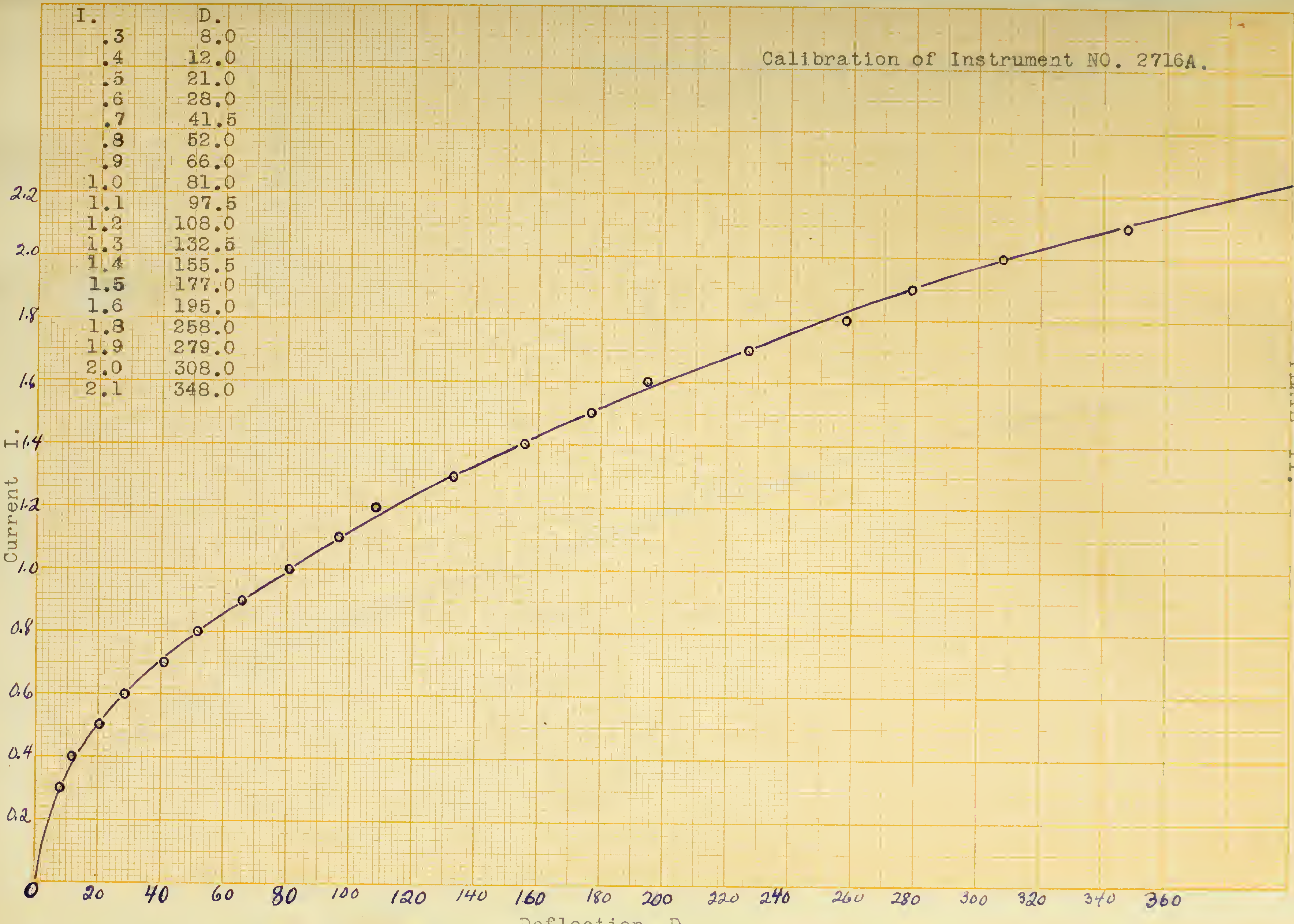


PLATE III.

Calibration Curve for Instrument No. 3764 E.

I.	D.
.20	11.0
.25	17.6
.30	26.0
.35	34.8
.40	45.6
.50	72.9
.60	101.0
.67	127.0
.75	157.4
.80	182.4

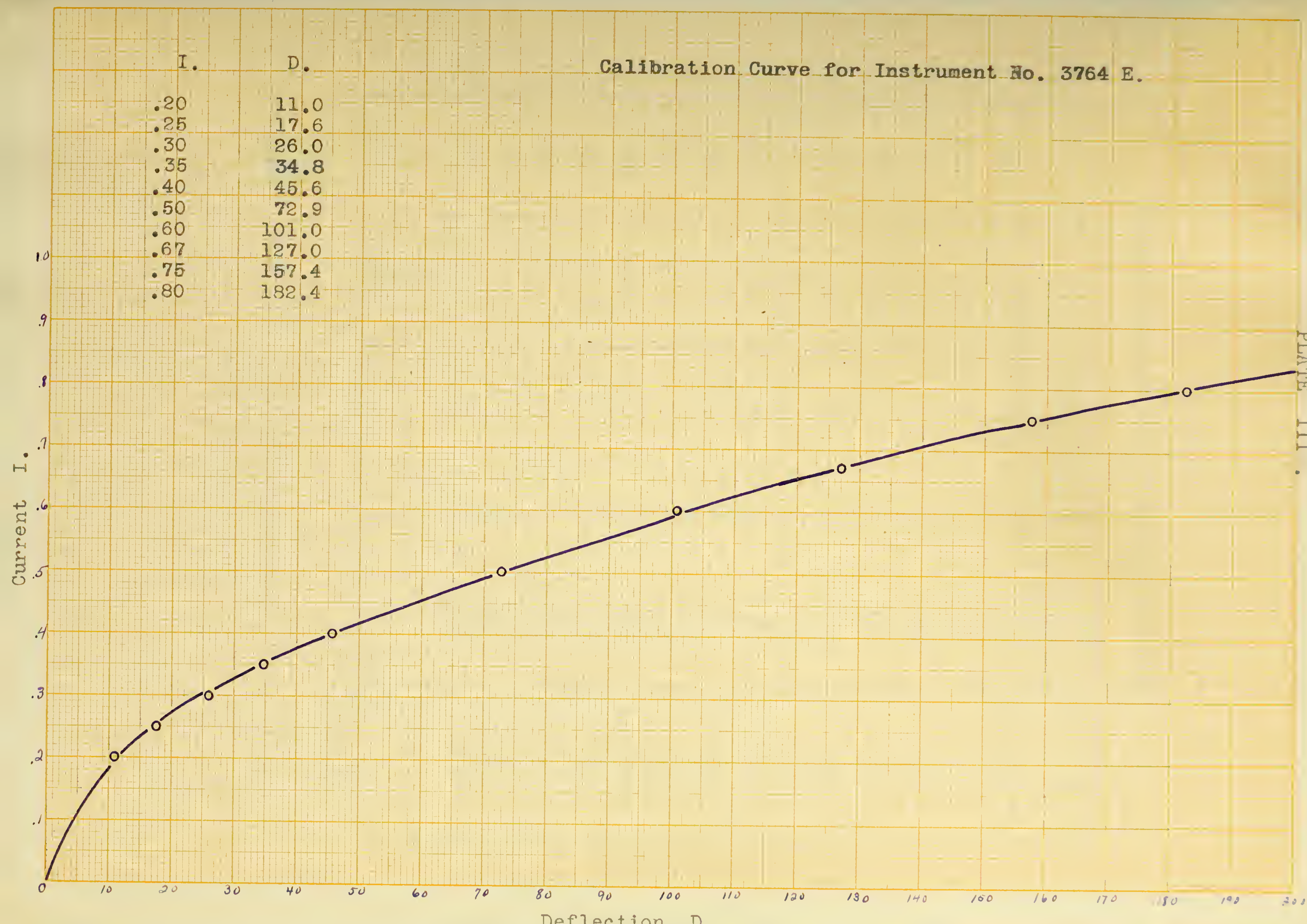


TABLE II

Calibration Data for Instrument No.3764F

I	D	From Curve $\sqrt{D}$	Corres-ponding I	$K = \frac{I}{\sqrt{D}}$
.08	2.0	1.4	.08	.0564
.10	3.2	2	.112	.0560
.12	4.3	3	.174	.0580
.14	6.0	4	.232	.0580
.16	7.8	5	.294	.0588
.20	12.0	6	.353	.0588
.24	17.0	7	.410	.0584
.30	26.5	8	.467	.0584
.36	38.0	9	.527	.0586
.42	51.0	10	.588	.0588
.48	67.5	11	.651	.0592
.52	79.0	12	.710	.0592
.60	103.8	13	.768	.0591
.70	140.3	14	.819	.0585
.75	161.3			
.812	192.9			

Average .0583

Resistance of pressure coil changeable due to poor contact at mercury cups.

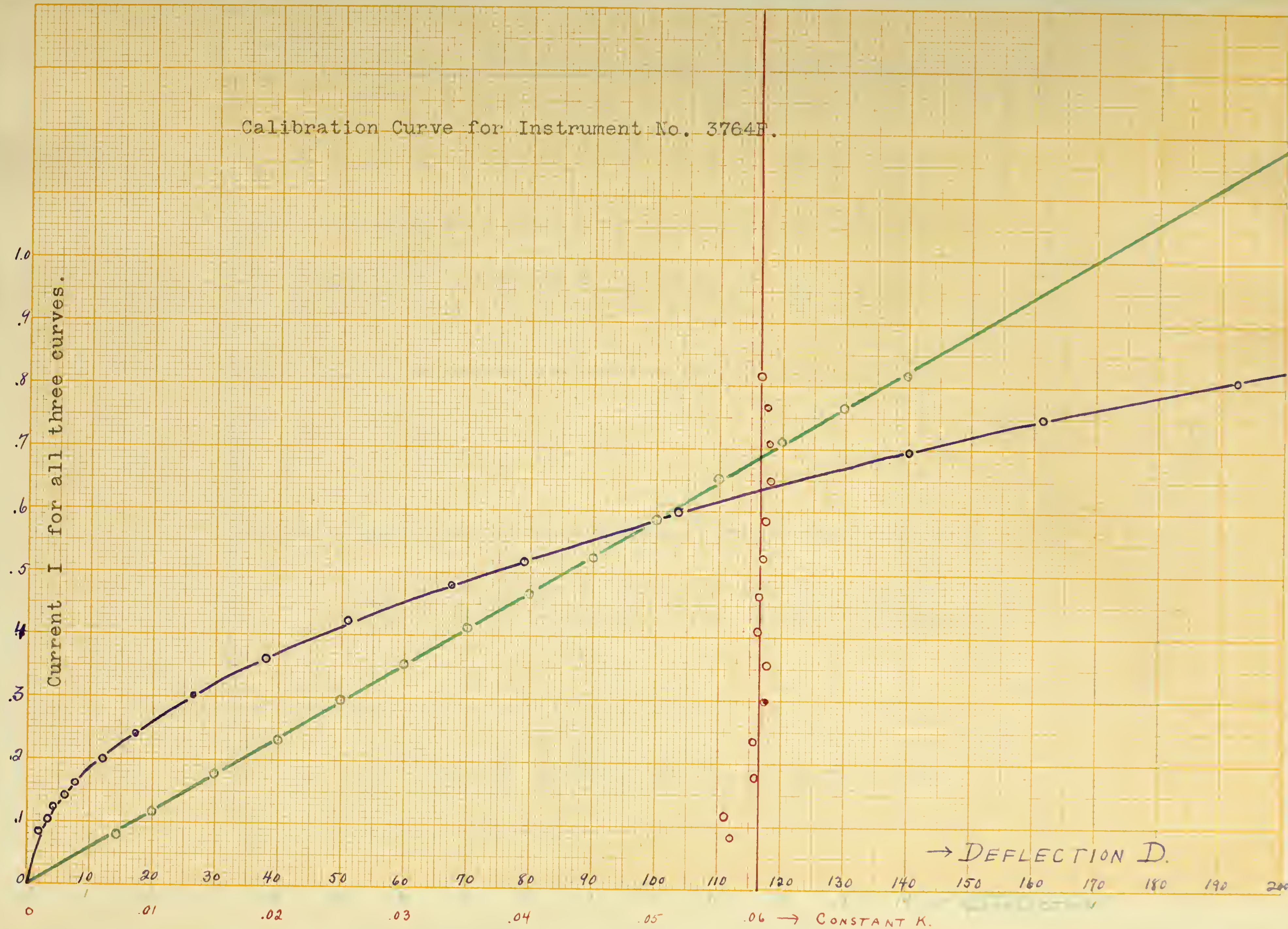

Calibration Curve for Instrument No. 3764F.
Current I for all three curves.
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
→ DEFLECTION D.
0
.01
.02
.03
.04
.05
.06 → CONSTANT K.

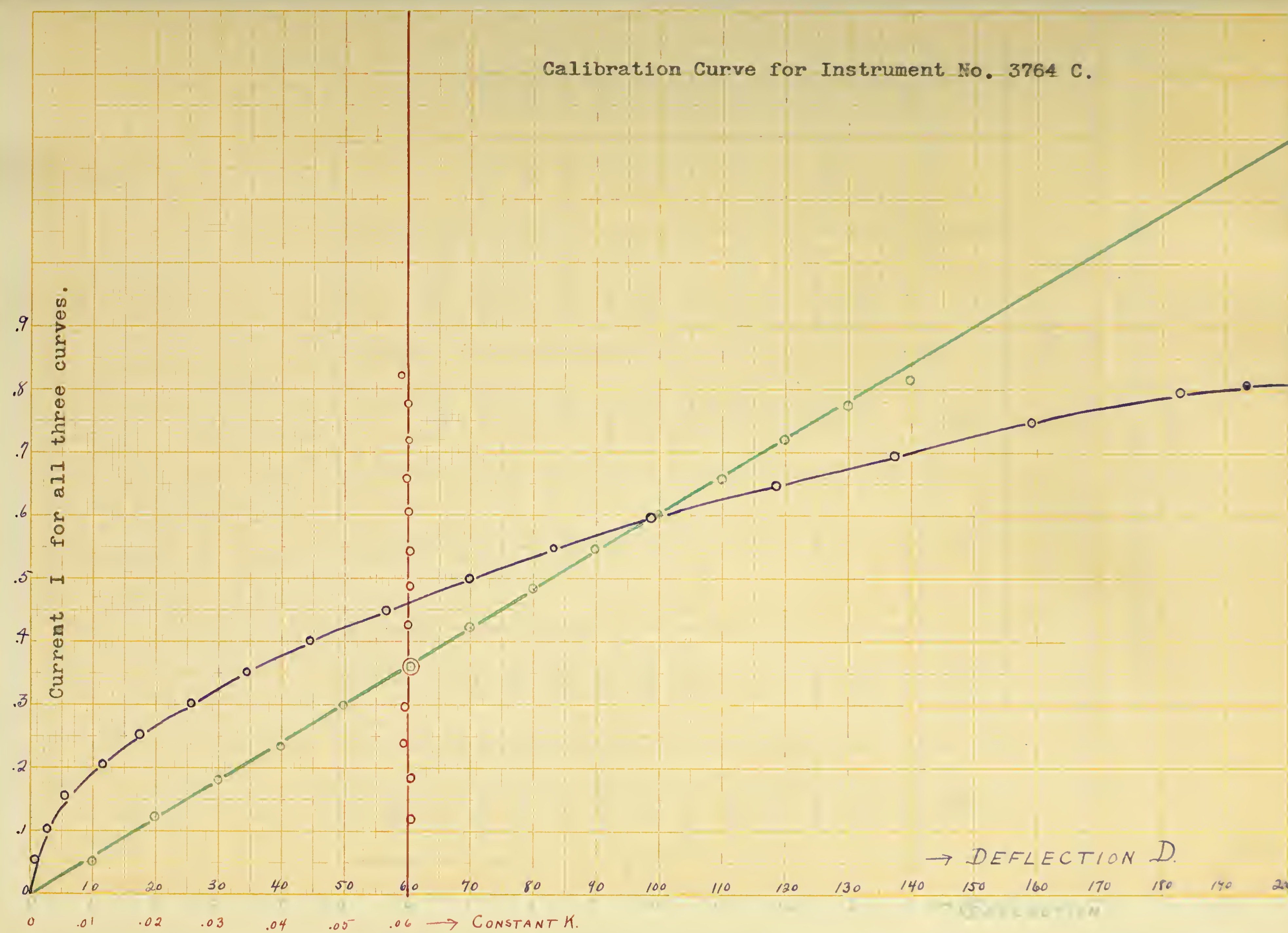
TABLE III

Calibration Data for Instrument No.3764C

Resistance of .75 shunt of ammeter as measured by testing set =.0236

R_c = .246 ohms R_p = 3.21   Average K = .0599

I	D	$\sqrt{D}$ from Curve	Corresponding I	$K=\frac{I}{\sqrt{D}}$
.10	3.2	2	.121	.0605
.15	6.0	3	.182	.0606
.20	11.7	4	.238	.0595
.25	17.7	5	.297	.0595
.30	25.8	6	.360	.0600
.35	34.8	7	.421	.0601
.40	44.8	8	.483	.0604
.45	56.7	9	.542	.0602
.50	70.1	10	.601	.0601
.55	83.6	11	.658	.0598
.60	99.0	12	.720	.0600
.65	119.0	13	.777	.0598
.70	137.5	14	.820	.0586
.75	159.6			
.80	183.0			
.813	194.0			



Calibration Curve for Instrument No. 3764 C.

TABLE IV

Calibration Data for Instrument 3764C'

R_c = .246 ohms R_p = 28.1 ohms For direct reading R = 781 ohms

K = .0358 K^2 = .00128

I	D	$\sqrt{D}$	$K=\frac{I}{\sqrt{D}}$	From Curve $\sqrt{D}$	Corresponding I	$K=\frac{I}{\sqrt{D}}$
.050	2.3			2	.073	.0365
.100	8.0	2.828	.0354	3	.109	.0363
.125	12.0	3.464	.0361	4	.145	.0363
.150	17.5	4.183	.0359	5	.181	.0362
.200	31.0	5.568	.0359	6	.216	.0360
.250	49.1	7.007	.0357	7	.250	.0357
.300	69.5	8.337	.0359	8	.287	.0359
.350	95.0	9.747	.0359	9	.324	.0360
.400	123.0	11.091	.0361	10	.359	.0359
.450	157.0	12.529	.0359	11	.397	.0361
.485	192.0	13.856	.0350	12	.436	.0363
		Average =	.0358	13	.464	.0357
				14	.490	.0350
					Average =	.03599

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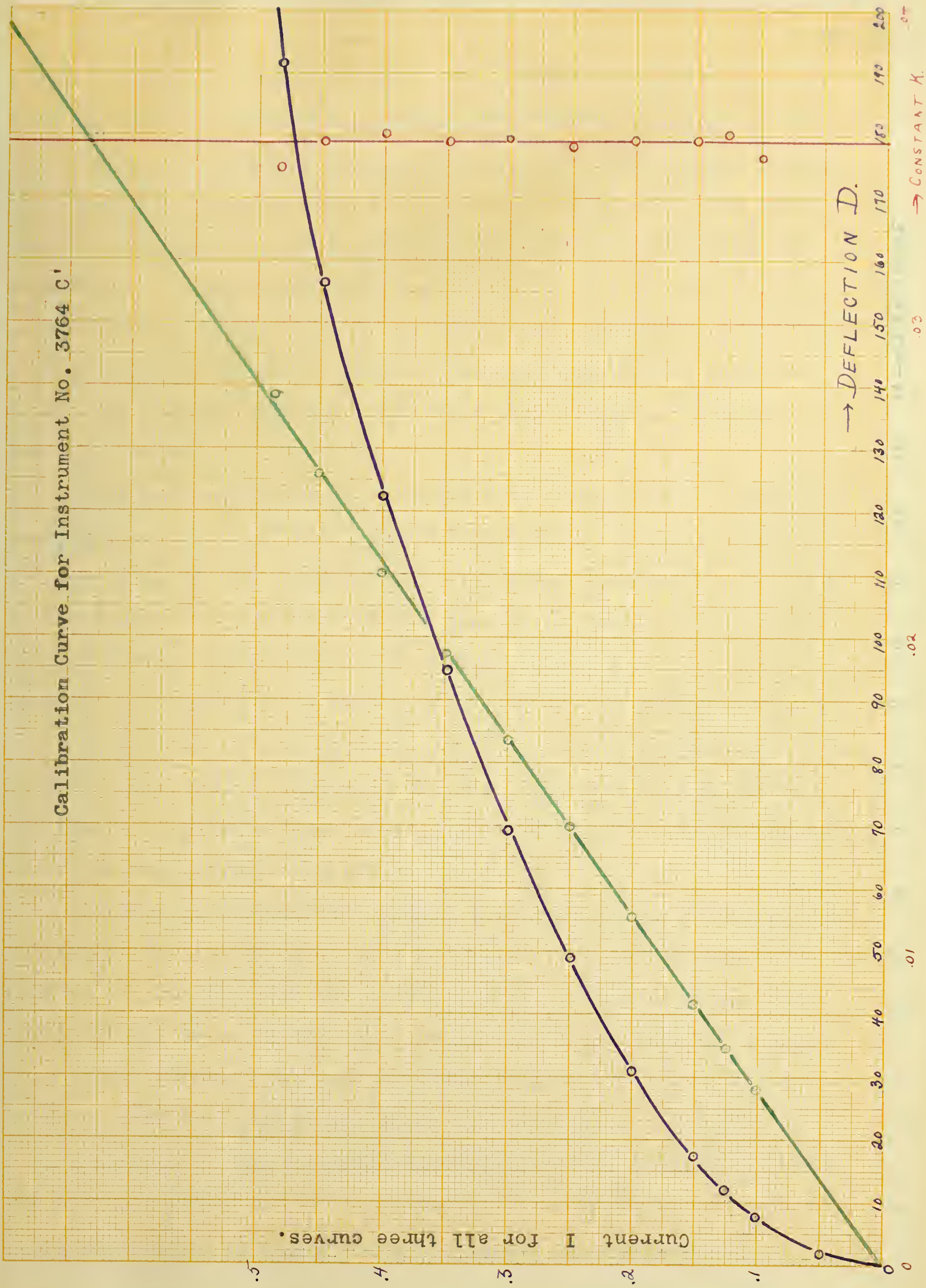
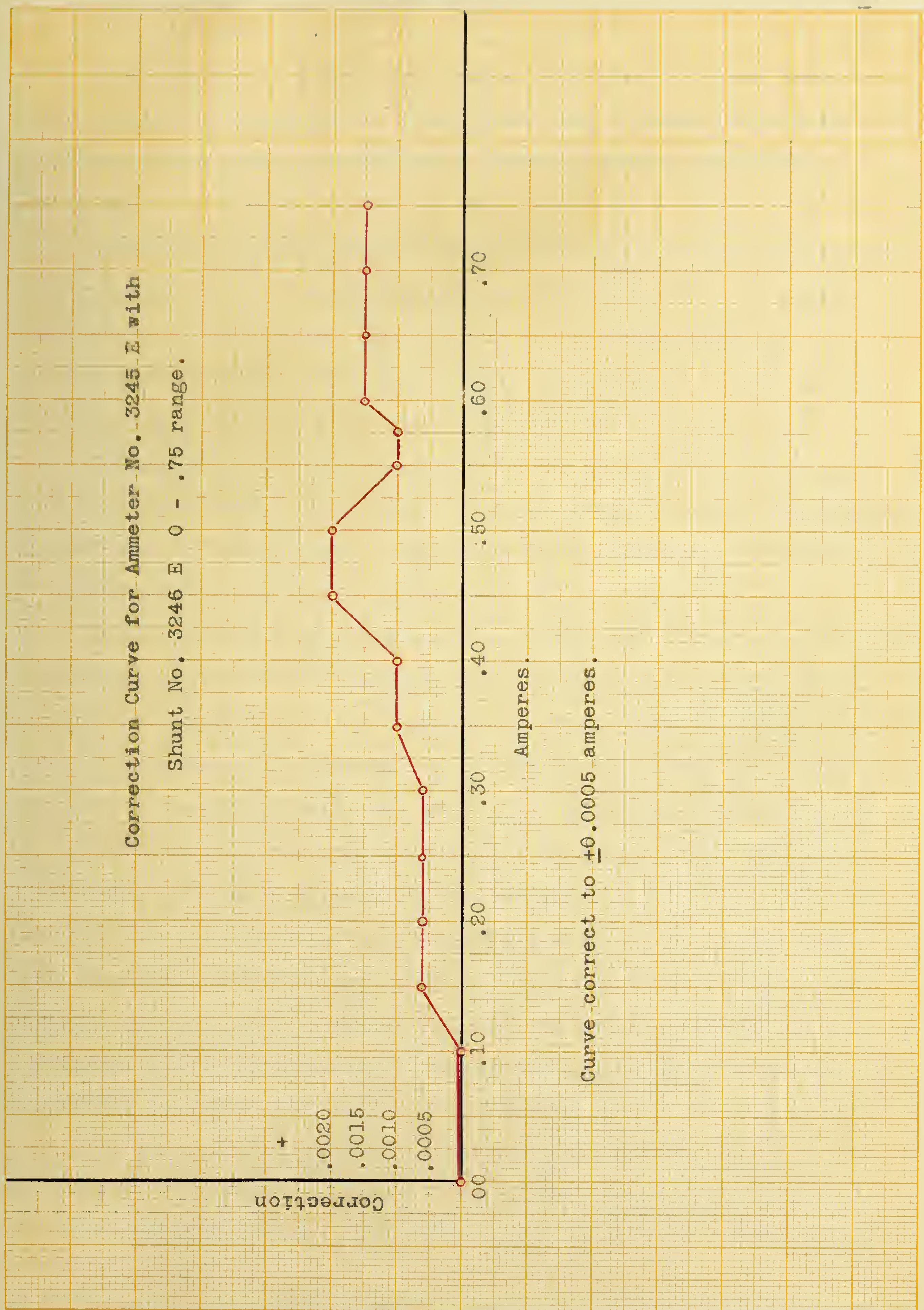

Calibration Curve for Instrument No. 3764 C'
Current I for all three curves.
→ DEFLECTION D.
→ CONSTANT K.
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
.01
.02
.03
.1
.2
.3
.4
.5

for Nos. 3764C and 3764F, it made the calculations easier to read from the curve a deflection D, which was a perfect square, so that when the square root was extracted, the result was a simple number. The current at these particular points were also noted, and hence when it came to calculating K, or $\frac{I}{\sqrt{D}}$, the work was to some extent simplified. In No.3764C' this was also done, but to see if this method introduced any error in K, the method of extracting the square root of each deflection D obtained from the calibration data, was used. The results, however, indicated very little difference, as Table IV shows.

Although No.3764F by its calibration curve seems to be almost exactly like No.3764C, still when it came to using it as a wattmeter and the value of the pressure coil resistance R_p needed to be known, it was found to be much in error. Instead of being in the neighborhood of 3 ohms, it was nearly 100 ohms. This was due to several causes, chief among which was poor contact at the mercury cups. In the amalgamation of the heavy wires which dip into these cups, nitric acid had been used and the wire had not been sufficiently cleaned afterwards, leaving mercury salts deposited in scales in the bottom of the cups and around the wires.

Ammeter : The ammeter used in the observations throughout the investigation was one of Siemens and Halske. A calibration curve was made of it, but the correction was so small (±.0005), being within the limits of error of the experiment, that no account was taken of it. Its calibration was made by comparison with a Weston Laboratory Standard Ammeter. Plate VII shows its calibration curve.

Voltmeter: The voltmeter was calibrated by means of a Leeds and Northrup Potentiometer and found to be accurate to one per cent. It was one of the Weston Electric Company's instruments.


Correction Curve for Ammeter No. 3245 E with
Shunt No. 3246 E 0 - .75 range.
Correction
+
.0020
.0015
.0010
.0005
00
.10
.20
.30
.40
.50
.60
.70
Amperes.
Curve correct to ±0.0005 amperes.

Resistance R_1: Since Queen boxes were used for this resistance, it was necessary to calibrate these too. A testing set was used for this purpose and the coils were found to be accurate to within 1%.

Mechanical Difficulties.- The first difficulty encountered was a broken circuit in the current coil of No.2323. This was easily remedied by soldering. In the process of repairing this the coil was also straightened. Not being wound on a bobbin, it had warped, and by placing it in a press, this deformation was corrected.

The perfect mechanical setting of the instruments under investigation was somewhat of a task. In some cases the set screw had to be loosened and the pointer readjusted so that the zero point of both pointers was accurately set at the zero of the dial.

The levelling of the instrument is important, for the slightest tipping to one side will introduce a frictional error in the movement of the current coil. In instrument 37640' this frictional error was the major cause of discrepancy of results for some time. For when the electrodynamometer was perfectly level and the leads from the movable coil dipped centrally into the mercury cups, there was a frictional resistance offered at the top and bottom of the coil. Then when the level was changed so as to avoid the latter, it was found that the leads to the mercury cups rubbed against the sides of the cups and brought about a frictional error. Hence to remedy it, the two places where the friction occurred were filed down so as to give freedom of movement. Thereafter the results were more in agreement.

The improper amalgamation of the movable coil leads, and the difficulty of uniform twisting of the spring have already been discussed. One other slight difficulty may be mentioned. It was found

that on taking out various plugs in the external resistance R_1, that even though it may add up to be the same as a resistance previously used when different plugs were out, there was a change in deflection. After both Queen boxes had all of their contacts cleaned with a German cleaning powder made especially for this purpose, this contact potential was eliminated.

V MANIPULATION

The first part of the investigation consisted in carrying out the various calibrations, and in selecting the particular instrument with which the subsequent work was to be done. After having worked with three of the instruments recently constructed in this laboratory, it was finally decided that better results would be obtained with the instrument when used as a wattmeter, if the movable coil would have more turns of finer wire.

This change was then made and it proved to be successful. It did not affect the use of the instrument as an ammeter except that it reduced the range of current to be measured, but it did make it so that it could not conveniently be used with the voltameters in the Junior Laboratory. For the best efficiency these cells should have about .7 of an ampere of current flowing through them, whereas the maximum current which can be sent through 3764C' is .485 ampere. This means that for a conveniently measurable amount of copper deposited, that the cell would have to be left in circuit for about 50 minutes; for as can be shown by substituting in the current equation on page 18.

$$I = \frac{\text{Gain in Wgt}}{\text{Time in sec. x .0003288 gms.}}$$

$$.485 = \frac{.5}{.0003288t} \quad \text{whence} \quad t = \text{minutes } 50 \text{ (approximately)}$$

The next step in the investigation was to connect the apparatus in the four different set-ups, two of which are shown below and the other two are Fig. 8 , page 19, and Fig. 10 , page 20. R_x is the resistance across which the consumption of power is measured and R_1,

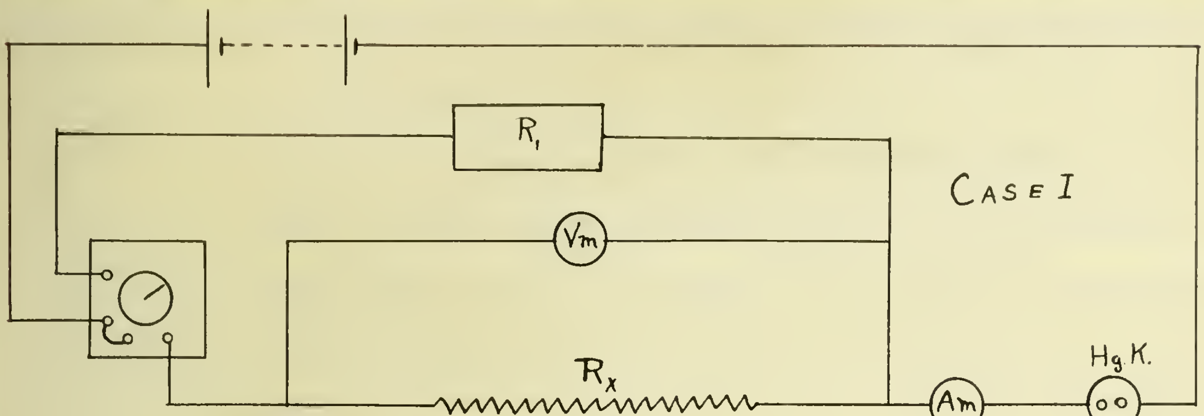


Fig. 12

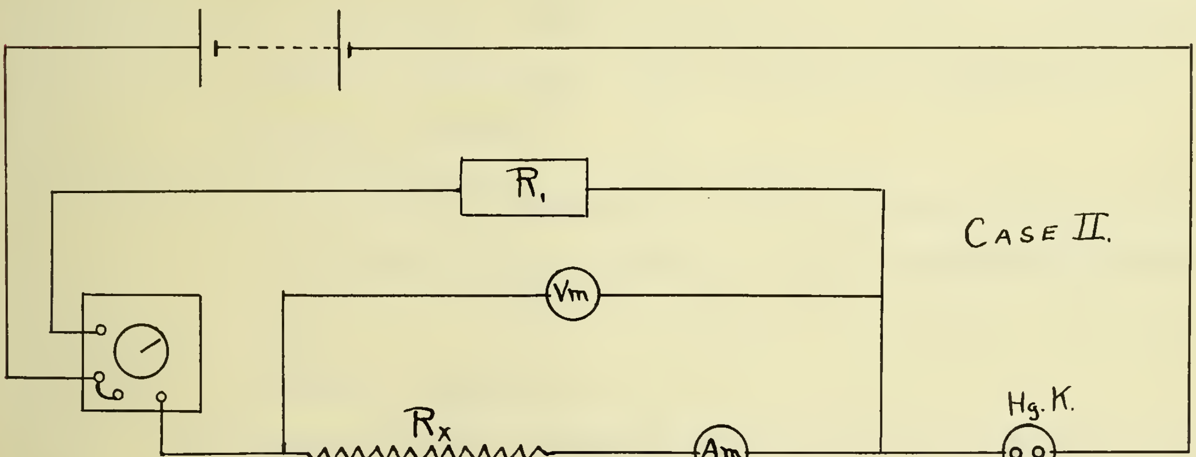


Fig. 13

Figs. 10 , 12, and 13 is the variable resistance which can be placed in series with the pressure coil R_p.

There was a considerable range of conditions with which to experiment, and for the purpose of clearness, it may be best to put these various changes in the following form, where each of the four set-ups will be discussed.

Fig. 12, page 39 Case I.

Here the electrodynamometer was used in connection with an

ammeter and voltmeter whose function was to check the values of the powers as measured by the electrodynamometer. First the resistances of R_c and R_p were measured by a testing set and then having made the set-up, the various manipulations were made in order to determine the best working conditions of the instrument. These manipulations were:

(1) One set of readings was taken with No.3764E, all the others being taken with No.3764C'. RK^2 variable, having R from 100 to 1000 ohms. R_x constant tin resistance also checked by constancy of results.

Also-

RK^2 constant, making instrument direct reading by having R_1 = 258 ohms. R_x variable tin resistance.

Results: Table V.

(2) RK^2 constant, having R_1 = 753 ohms and thus making the instrument direct reading. R_x a variable tin resistance.

Results: Table VI.

(3) RK^2 variable, having R from 500 to 2000 ohms. R_x a constant tin resistance also checked by constancy of results and ammeter and voltmeter only.

Results: Table VIII.

(4) Same as data taken in (2) except that much smaller power consumption was measured.

Results: Table IX.

(5) RK^2 constant making the instrument direct reading. R_x variable lamp resistance. Also checked by specified watts of the lamps.

Results: Table Xb.

Fig. 13, Page 39 Case II

Since there was some lack of agreement in the results as obtained above, due to the ammeter not reading the current through R_x only, it was thought advisable to see if better results would follow by placing the ammeter in the position as shown in this set-up. The ammeter in Case I had been reading the current through three branches, R_x, Vm., and R_1, but the voltmeter was measuring the true voltage across R_x. A correction formula developed from Kirchoff's law of divided circuits was applied to the results of Case I, but it did not adequately account for the discrepancy. In Case II the ammeter reading was correct, but the voltmeter was now measuring the drop across R_x and the ammeter. This, however, introduced no appreciable error for the resistance of the ammeter was negligible in comparison with resistance of the lamps.

Three sets of readings were taken with this set up.

(1) RK^2 constant making the instrument direct reading.
R_x variable lamp resistance. Also checked by watts as specified on the lamps.
Results: Table XII

(2) RK^2 variable, having R from 300 to 1000 ohms.
R_x constant lamp resistance, also checked by the constancy of results and specified watts of the lamps.
Results: Table XIII

(3) Same as data taken in (2) except that greater power consumption was measured.
Results: Table XIV

Fig. 10 , page 20

In order to find out whether the electrodynamometer was at fault, readings were then taken using the instrument only, to measure

wattage consumed by incandescent lamps. Four sets of data were taken as follows:

(1) RK^2 variable, having R from 100 to 500 ohms. R_x a constant tin resistance checked by constancy of results.
Results: Table VII

(2) RK^2 constant, making the instrument direct reading. R_x a variable lamp resistance. Checked by specified watts of the lamps. Results: Table Xa.

(3) RK^2 variable, having R from 350 to 5000 ohms. R_x a constant 25 watt lamp resistance. Checked by constancy of results and specified watts of the lamp.
Results: Table XIa.

(4) RK^2 variable, having R from 500 to 5000 ohms. R_x a constant 40 watt lamp resistance. Checked by constancy of results and specified watts of the lamp.
Results: Table XIa.

Fig. 8, page 19

The one thing left to be done now was obviously to measure power by using the ammeter and voltmeter only. Since there was a discrepancy of results when the one reading of this nature was taken as a check on the data of Tables VIII and IX, it was considered worthy of attention to see how accurate the ammeter-voltmeter method is. Table Xc shows the data taken. Here the power was measured across various lamps and the results checked by their specified wattage.

The sources of current in this experimental work were two. Whenever the incandescent lamps were used, current was drawn from the 110 volt D.C. mains, while in all other cases the storage batteries maintained the required current.

TABLE V

Electrodynamometer No.3764E as Wattmeter

R_p = 3.2 R_c = .2 K = .059 K^2 = .00349

Power measured across a constant tin resistance

Checked simultaneously with ammeter and voltmeter

I	E	$R=R_1+R_p$	D	Watts EI	Watts RK^2D
2.500	7.4	1000	3.7	18.500	12.923
2.500	7.4	900	4.3	18.500	13.545
2.500	7.4	800	6.0	18.500	16.800
2.525	7.4	700	6.2	18.685	15.190
2.500	7.5	600	8.0	18.750	16.800
2.500	7.5	500	9.5	18.750	16.625
2.525	7.5	400	11.9	18.938	16.660
2.550	7.3	300	17.0	18.615	17.850
2.550	7.3	200	26.0	18.615	18.200
2.550	7.3	150	34.5	18.615	18.113
2.575	7.2	100	52.6	18.540	18.410
	Direct reading, R_1 = 258, R_x Variable				
2.75	8.0	260.74	23.9	22.000	23.9
2.05	7.5	260.74	15.5	15.375	15.5
1.60	6.5	260.74	10.0	10.400	10.0

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The remaining data sheets are for instrument No.3764C' and all except the last one, page 47, refer to Case 1.

TABLE VI

Electrodynamometer as a Wattmeter

Direct reading $RK^2 = 1$

Checked simultaneously with ammeter and voltmeter

Power measured across a variable tin resistance

I	E	EI	D
1.2	20.0	24.0	24.0
1.3	19.6	25.5	24.5
2.0	18.5	37.0	37.0
3.0	17.4	52.2	51.2
10.0	8.0	80.0	99.0*

*current coil hot

TABLE VII

RK^2 Variable

Ammeter and voltmeter omitted

Power measured across a constant tin resistance

$R = R_1 + R_p$	D	Watts=RK^2D
100	160.0	20.431
128	124.7	20.880
200	79.0	20.224
300	53.0	20.352
400	39.0	19.968
500	31.0	19.840

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TABLE VIII

Electrodynamometer as a Wattmeter

RK^2 Variable......K = .0358.........K^2 = .00128......R_p = 28.1

Checked simultaneously with ammeter and voltmeter

Power measured across a constant tin resistance.

I	E	$R=R_1+R_p$	D	Watts EI	Watts RK^2D
2.02	41.0	500	145.5	80.82	93.12
1.99	41.5	781	86.5	82.59	86.50
1.99	41.5	800	75.4	82.59	77.21
1.95	41.5	2000	30.0	82.56	76.80

Using ammeter and voltmeter only

I = 2.2: E = 46: Watts = 101.2

TABLE IX

I	E	$R=R_1+R_p$	D	Watts EI	Watts RK^2D
1.04	19.	200	99.0	19.76	25.34
.99	19.	300	59.0	18.71	22.66
.96	19.	400	41.0	18.24	20.99
.95	19.	500	31.6	18.05	20.22
.94	19.	600	25.9	17.86	19.89
.936	19.	700	21.7	17.78	19.44
.925	19.	781	19.0	17.58	18.99
.925	19.	900	17.8	17.58	20.51
.925	19.	1000	15.4	17.58	19.71
.920	19.	1500	9.8	17.48	18.81
.920	19.	2000	7.0	17.48	17.92
.920	19.	3000	4.5	17.48	17.28
.912	19.	4000	3.0	17.33	15.36
.896	18.5	5000	2.3	16.58	14.72
.896	18.5	8950	1.0	16.58	11.46

Using ammeter and voltmeter only

I = .84 E = 17.5 Watts = 14.7

TABLE IX

Measurement of Power Consumed by a Variable Bank of Lamps

Electrodynamometer Direct Reading $RK^2 = 1$

a: By electrodynamometer R_1 = 753 ohms *Old lamps			b: By electrodynamometer checked simultaneously with ammeter and voltmeter				c: By ammeter and voltmeter		
Lamp No.	Specified Watts	Observed Watts	I	E	Watts = EI	Watts D	I	E	Watts EI
1	25	25.0	.38	117	44.46	24.5	.22	111	24.42
2	25	25.5	.36	110	39.60	24.0	.22	111	24.42
*3	40	39.0	.37	109	40.33	36.0	.34	111	37.74
4	40	40.5	.50	113	56.50	38.8	.36	111	39.96
5	40	40.0	.49	108	52.92	37.5	.36	111	39.96
*6	25	23.5	.34	109	37.06	22.0	.20	111	22.20
1&2	50	51.0	.58	110	63.80	57.2			
4&5	80	82.0	.87	115	100.05	82.2			
1-4inc.	130	133.0							
1-5inc.	170	173.0							

TABLE X

Measurement of Power Consumed by an Incandescent Lamp

Varying R_1, keeping R_x constant, and dispensing with

Ammeter and Voltmeter

a: R_x = 25 watt lamp No.1				b: R_x = 40 watt lamp No.4		
$R=R_1+R_p$	D	$Watts=RK^2D$		$R=R_1+R_p$	D	$Watts=RK^2D$
350	55.0	24.64	R_p = 28.1	500	61.0	39.04
400	46.0	23.55		550	60.0	42.24
450	41.6	23.96	K = .0358	600	50.5	38.78
500	38.0	24.32		700	43.5	38.98
550	42.0	29.47	K^2 = .00128	781	40.0	39.99
600	38.5	29.47		900	36.0	41.47
650	35.7	29.70	Means	1000	32.0	40.96
700	32.8	29.39		1500	20.5	39.36
781	23.5	23.49	No.1 = 26.43	2000	15.5	39.68
800	23.5	24.16		3000	11.0	42.24
1000	20.8	26.62	No.4 = 40.45	4000	7.5	38.40
3000	7.6	29.18		5000	6.6	42.24
5000	4.0	25.60				

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TABLE XII

$RK^2 = 1$	Direct reading		R_x variable lamp resistance		
Lamp No.	E	I	Watts EI	Watts D	Watts Specified
1	112.0	.220	24.64	24.0	25
1,6	112.0	.424	47.49	46.2	50
1,2,6	111.5	.645	71.92	70.4	75
1,2,4,6	111.4	.998	111.18	108.0	115
1,2,4,5,6	111.4	1.350	150.39	146.5	155

TABLE XIII

RK^2 variable	R_x constant at two 25 watt lamps Nos. 1 and 2				
I	E	$R=R_1+R_p$	D	Watts EI	Watts RK^2D
.440	112.0	300	126.0	49.28	48.39
.440	112.0	400	95.3	49.28	49.76
.441	112.0	500	78.2	49.39	50.00
.442	112.2	500	75.0	49.59	48.30
.442	112.2	500	76.0	49.59	48.64
.442	113.0	600	66.2	49.95	50.84
.443	113.2	600	66.3	50.16	50.92
.443	113.0	781	50.0	50.06	49.98
.445	113.4	1000	39.5	50.46	50.56

TABLE XIV

RK^2 variable	R_x constant at two 40 watt lamps Nos. 5 and 6				
I	E	$R=R_1+R_p$	D	Watts EI	Watts RK^2D
.710	110.0	1000	60.0	78.10	76.80
.710	111.2	1500	41.0	78.95	78.62
.712	112.1	2000	31.5	79.82	80.64
.720	114.0	2500	25.0	82.08	80.00

VI DISCUSSION OF RESULTS

As has already been mentioned in the introduction, there is a considerable amount of disagreement in results, but nevertheless, conclusive data has been obtained to make sure of the best conditions under which the electrodynamometer should be operated as a wattmeter.

It seems as though the resistance R_1 required to make the instrument direct reading was the critical resistance at which the electrodynamometer gave the most accurate results, for in all of the experimental work this was the case.

Another peculiarity about the results obtained was the variation in the watts as indicated by the electrodynamometer with change of resistance R_1 in series with the pressure coil. When used with the ammeter and voltmeter as shown in Case I Fig. 12, there was a marked decrease in the electrodynamometer power measurement with an increase of R_1, while the product EI practically remained constant. Tables V, VIII and IX show this very clearly. However, when the set-up was changed to Case II, Fig. 13, the reverse was true, but the decrease was not so conspicuous, as can be seen by an examination of Tables XIII and XIV. When the electrodynamometer was used alone, no such variation could be noted. Hence the resulting conclusion is that this external resistance is not acting the same as if it were in the pressure coil itself and there is a maximum and minimum limit to the value of R_1. These limits seem to merge into one, and that one is that R_1 be just the resistance necessary for making the instrument direct reading.

It can readily be seen by comparison of the data tables for Case I with those of Case II, that the latter is by far the better arrangement. Take for example Table VIII and compare it with Table

XIV. In the former for a measurement of about 82.5 watts the electrodynamometer gave readings from 76 to 93, while in the latter for a measurement of 80 watts, the electrodynamometer varied no more than the EI measurement and then only through the small range of 77 to 81. The data taken when the electrodynamometer alone, or the ammeter and voltmeter alone were used give evidence of the fact that neither method was at fault, but when one came to putting the two methods together, having one act as a check on the other, then he encountered some difficulties.

Sources of Error. In addition to the errors already mentioned, the one major error has yet to be discussed. Obviously the electrodynamometer consumes some power in its current and pressure coils and the inaccuracy introduced thereby is in some cases sufficient to make necessary a correction. The current flowing through the current coil of the electrodynamometer is the sum of the load current and of the current consumed in the pressure coil of the wattmeter itself because the potential leads are on the "line" side of the current coil. Therefore, the instrument indicates less power than is actually consumed in the load. This was true of all the data taken, for in practically every case the power as measured by the electrodynamometer was too low.

Some wattmeters are provided with a compensating winding which makes a correction unnecessary, and thus simplifies the use of the instrument. This compensating coil is connected in series with the pressure coil. When the load is zero, a current flows through current and pressure windings of the wattmeter, and causes the pointer to indicate some power, though in reality the power consumption is zero. The function of the compensating coil is to give a number of

ampere-turns equal and opposite to that created by the current coil, and thus make the pointer indicate zero at no load. The compensation is good at all voltages, since the current in the compensating coil is always the same as the pressure coil (at no load).

Another source of error was the fluctuating of the voltage and current derived from the 110 volt D.C. mains. This fluctuation made it impossible to secure accurate simultaneous readings of the wattmeter, ammeter and voltmeter, for after the wattmeter deflection was read, one had to walk the length of the table before the ammeter and voltmeter readings could be obtained and these may have changed in the meantime.

The remaining errors were those of observation, that is, the accuracy with which the ammeter, voltmeter, and electrodynamometer could be read. The ammeter by use of various shunts could be read accurately to .1 and in some cases to .01 of an ampere; the voltmeter to probably .3 of a volt, and the electrodynamometer to .2 of a division.

VII CONCLUSION

This investigation has led to the finding of the best conditions under which electrodynamometer No.37640' should be operated. The following conclusions can be drawn:

(1) The instrument works best when direct reading and within a range of from 18 to 175 watts.

(2) It can be checked simultaneously with an ammeter and voltmeter quite accurately if the voltmeter is shunted across the translating device and ammeter as in Case II. The range of resistance R_1 to be placed in series with R_p depends of course on the power measured, but it can